Research and Development to Improve Naval Shipboard Waste Management Using Compact, Closed-Loop Controlled Waste Incinerator

Final Report
Actively Controlled Afterburner
Integration with Commercial TeamTec GS500 Incinerator

Contract N00014-96-C-0105

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Introduction

The US Navy commitment to environmentally clean ships require that the present practices of waste storage and off loading and overboard discharge be eliminated. Thermal waste treatment onboard Naval vessels is preferred as it accomplishes many waste processing goals including volume reduction, sterilization and detoxification. It is also cost-effective and among the safest approaches requiring little specialized personnel training. Unfortunately existing seaworthy incinerator designs that meet the Navy's size and weight limitations are not expected to meet the International Maritime Organization (IMO) standards when operating under the higher throughput demands of future target shipboard operations. This has led to the exploration of novel approaches, such as the use of forced acoustics, in order to maintain compact incineration systems capable of increased waste throughput.

Energy and Environmental Research Corporation (EER) and the Naval Air Warfare Center Weapons Division (NAWCWD) have developed a forced acoustic afterburner that improves heat transfer, turbulent mixing and firing density. The afterburner designed incorporates a central air jet issuing past a dump plane. The forcing frequency of the air jet is controlled to match the jet's natural frequency causing formation of coherent vortices in the afterburner chamber, as illustrated in Figure 1. Air-starved reaction products enter circumferencially around the air jet and are entrained into the shedding vortices, mixing the reaction products with the air through strain-enhanced diffusion and convection. Ignition of the gases is strain-delayed allowing enhanced mixing, lower peak flame temperatures and the elimination of cold fuel pockets. This combustion mechanism reduces products of incomplete combustion and lowers formation of oxides of nitrogen (NOx).

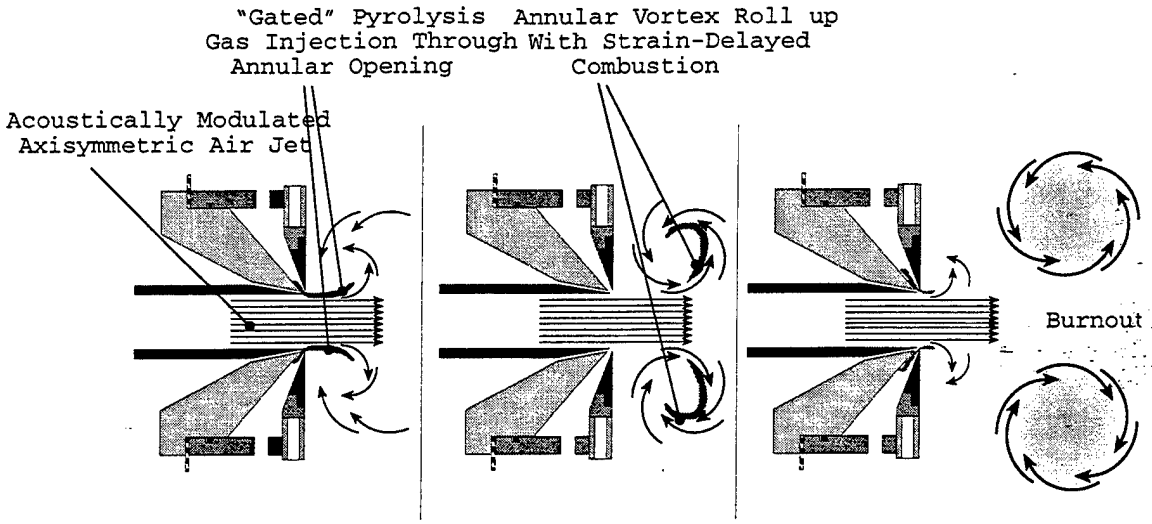

Figure 1. Progression illustrating incipience, roll-up and shedding of vortices induced by an axisymmetric jet issuing at a dump plane. Fuel is shown to entrain into the vortex with effective mixing and strain-delayed combustion resulting in a lifted premixed-like flame.

EER and NAWCWD have conducted a shore-based demonstration of the Actively Controlled Afterburner integrated with a commercial marine incinerator supplied by TeamTec of Norway. The marine incinerator was modified to serve as the primary air-starved chamber pyrolyzing streams ranging from propane to solid waste. Test results show that the waste throughput capacity of the incinerator can be more than doubled while emissions remain well below IMO standards. Equally important, the tests demonstrated that the afterburner was capable of handling a variety of pyrolyzed waste products and of operating over a wide range of pyrolysis gas heat values without exceeding IMO emission standards or causing burner outages. Also during demonstration, system controls were identified that would further control carbon monoxide (CO) and NOx emissions, simultaneously.

Background

The Actively Controlled Afterburner is a forced combustion system that provides rapid fuel and air mixing and delayed combustion. The principle of operation involves the formation of coherent jet vortices issuing into a chamber. Fuel entrains circumferentially into the vortices where rapid and thorough mixing with air occurs. Combustion of the air

and fuel mixture is strain-delayed which allows further development of a well-mixed combustible gas as compared to free jets where boundary mixing and combustion dominates. The vortex mixing avoids local high and low temperatures where pollutant species can form or escape destruction. While emissions are low, the real advantage of the Actively Controlled Afterburner, is its compact size. The afterburner can achieve excellent burnout in an afterburner chamber volume that is 10 to 30 times smaller than conventional afterburner designs. The afterburner tested in the recent shore-based demonstration had a design residence time of 67 msec compared with the conventional afterburner residence times of 1 to 2 seconds.

Because of the significant reduction in afterburner size, the combined volume of the primary and afterburner chambers are significantly smaller than a conventional fuel-lean incinerator chamber for the same waste processing capacity. Regulations for incinerator designs often require a 1 to 2 second gas residence time to ensure complete burnout. This limits the firing density to around 260 to 520 kW/m^3. When a primary chamber is operated in air-starved mode, a significant volume reduction is achieved because the air flow is reduced by a third and a 1 to 2 second residence time for complete burnout is no longer required. Theoretically the residence time in the primary chamber can be low, however, to avoid particulate matter entrainment into the product gases, gas residence times are usually not drastically reduced below 1 to 2 second. For a 1 second residence time, the firing density of an air-starved primary chamber can increase by a factor between three and six. This allows a combined firing density of 1,200 kW/m^3 for the primary and Actively Controlled Afterburner chambers. Therefore, the total heat input increases by two to five times for a system of comparable size.

Afterburner Development

The Actively Controlled Afterburner was developed from laboratory-scale power levels of 5 kW to the most recent full-scale demonstration levels of 750 kW. Experiments conducted in the laboratory investigated vortex enhanced mixing and combustion utilizing advanced laser diagnostics[1]. The afterburner development began with a precision engineered afterburner utilizing knife-edge annular slots through which fuel flow was

phase controlled (gated) into the vortex roll-ups. In the forced acoustic mode, the afterburner demonstrated up to 5 nines (99.999%) destruction efficiency of benzene and simultaneous reduction of CO and NOx. The benzene destruction represented a 10 to 20 fold reduction in emissions over the unforced operation. Further evaluation with composite phase locking imaging fluorescence (PLIF) revealed fuel and air mixing behaviors and additional OH imaging identified the combustion zone and led to an understanding of the combustion mechanisms[2]. These advanced diagnostic tools showed the impact of gating fuel into the right temporal location of the vortex. OH imaging was also able to capture the fundamental differences in flame structure for a properly operated forced acoustic burner and clearly showed the difference between the forcing-enhanced strain-delayed combustion over the unforced standard diffusion flame combustion[2].

After successful results at the laboratory-scale and based on the detailed understanding of fluid dynamics, combustion and acoustic interactions, a 50 kW pilot-scale afterburner was constructed. The testing at this scale provided clear evidence of the advantage of forcing[2]. Without forcing the afterburner flame was seen to be long and lazy. Immediately upon forcing the air, the flame appears to attach above the burner face and become very intense and shorter. The compactness of the system was also evident. Complete burnout was achieved in an afterburner firing density of 6,500 kW/m^3 which is an order of magnitude improvement over standard afterburners.

At the 50 kW scale, self modulating (natural gating) of fuel by vortex entrainment was also observed. The work showed that air forcing alone would improve destruction efficiencies over unforced operation. This paved the way to a simplified afterburner design that eliminated hot fuel gating and phase control.

Development efforts also involved operations on a variety of waste fuel compositions. Initial work was carried out with a 58.9 MJ/m^3 (1580 BTU/ft^3) mixture of nitrogen, ethylene, and benzene at ambient conditions. To test the concept for pyrolysis gas characteristics, the fuel heat value was reduced to as low as 5.66 MJ/m^3 (152 BTU/ft^3) and the temperature was raised to 540°C. The fuel slot was adjusted to maintain the fuel

jet velocities. In this configuration, the unit continued to produced strong vortices, a stable blue flame and low emission. Further testing with more realistic pyrolysis fuel components comprising 18% CO, 10% water, 20% hydrogen, and 52% nitrogen was conducted. The fuel was fed to the burner at 340°C. The burner continued to perform well with stable flame and low emissions.

Large-scale tests on a 500 kW afterburner were conducted at EER to optimize forcing parameters while operating on a simulation waste stream of pyrolyzed propane. A low pressure drop hot-gas scroll burner was built by EER and installed on a low volume afterburner chamber (Figure 2). The afterburner operated at a firing density of 4,800 kW/m^3. During these tests, applying forcing and varying the forcing frequency was able to effect large reductions in CO emissions as shown in Figure 3. The minimum CO level obtained was 70 ppm (corrected to 7% O_2) at a forcing frequency of around 220 Hz. The total hydrocarbons (THC) were at the detection limit (1 ppm). NOx emissions were 50 ppm (corrected to 7% O_2). Despite the heavy soot loading to the afterburner, no soot was visible in the afterburner exhaust.

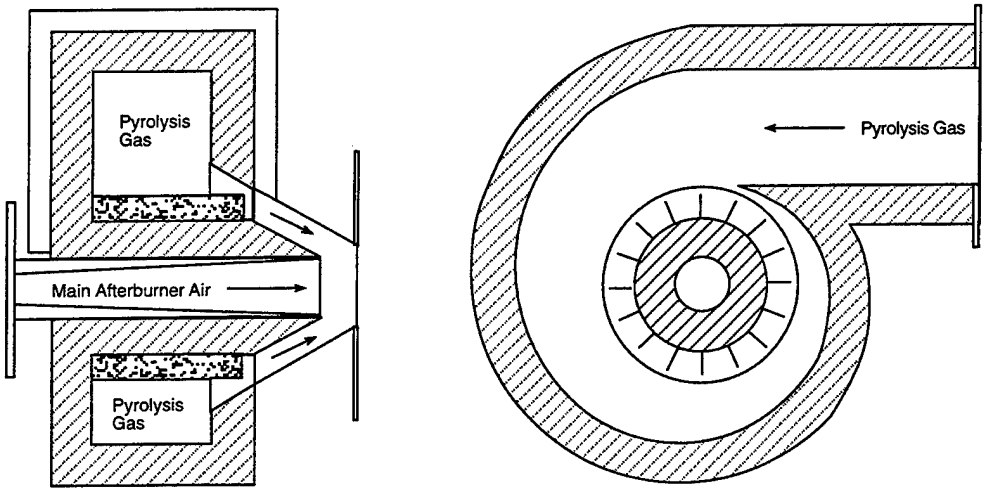

Figure 2. 500 kW Afterburner incorporating a low pressure drop scroll chamber.

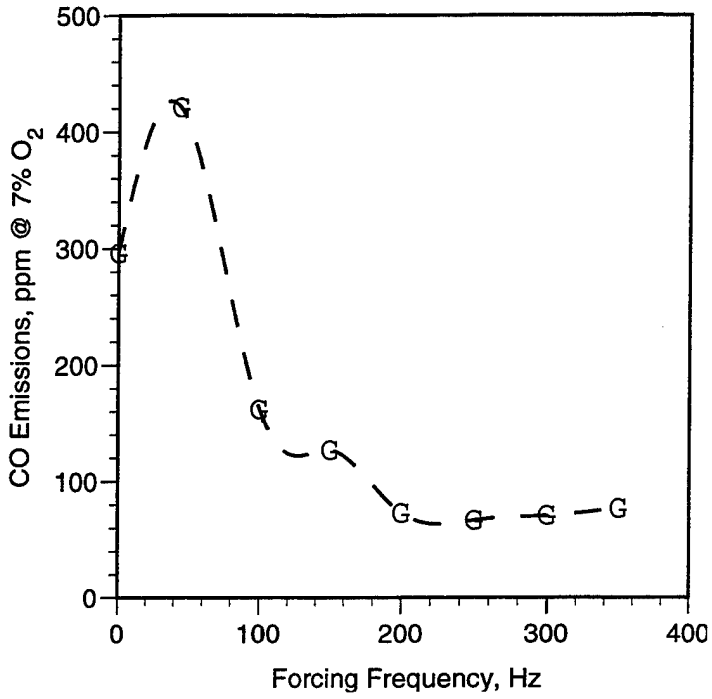

Figure 3. Scroll afterburner CO emissions at varying acoustic forcing frequencies.

To further the transition to realistic solid waste operation, a commercial marine incinerator was modified for use as a solid waste pyrolysis chamber and a new simplified afterburner was installed. The following sections present the work and results of the solid waste pyrolysis and afterburning demonstration.

Technical Objectives: The Actively Controlled Afterburner has been developed from laboratory to full-scale utilizing a variety of fuels as the waste pyrolysis products. The latest demonstration of the afterburner integrated with a modified marine incinerator was directed towards thermal processing of solid wastes of similar compositions to those anticipated onboard US Naval vessels.

The goal of the demonstration was to double the waste throughput capacity of a commercially available marine incinerator while reducing emissions. A Golar GS500C incinerator manufactured by TeamTec, SA of Norway was shipped to EER and modified to serve as the primary chamber. The baseline incinerator capacity and emissions were

stipulated in an IMO Certificate of Compliance Report[3] that set the maximum IMO class 2 solid waste loading at 195 kW and the achievable CO emission at 122 mg/MJ (approximately 256 ppm @ 7% O_2).

Another practical goal of the demonstration was to discover any potential limitations of the afterburner to handle pyrolysis products from solid waste that can include large unburned particles, heavy soot and particle loadings, and fluctuating pyrolysis fuel compositions.

System Configuration: TeamTec's model GS500C marine incinerator was shipped to EER and installed at their Test Site in Irvine, California. The GS500C is a conventional fuel-lean incinerator that was field modified for air-starved operation to serve as the primary pyrolysis chamber for the afterburner. Modifications involved plugging air intake openings and operating at lower induced draft pressure to reduce air intake. The GS500 diesel burner, with a maximum firing capacity of 450 kW, was restricted to a constant firing rate of 142 kW. A photograph of the Test Site installation is presented in Figure 4. The cooling air, that is normally mixed with the exhaust products at the GS500 exit, was routed away and the exhaust products, indicated by the arrow in Figure 4, were delivered through a short transition duct to the afterburner. Auxiliary propane fuel injected into the transition duct was incorporated for shakedown, solid waste switching and attempted pyrolysis heat value control.

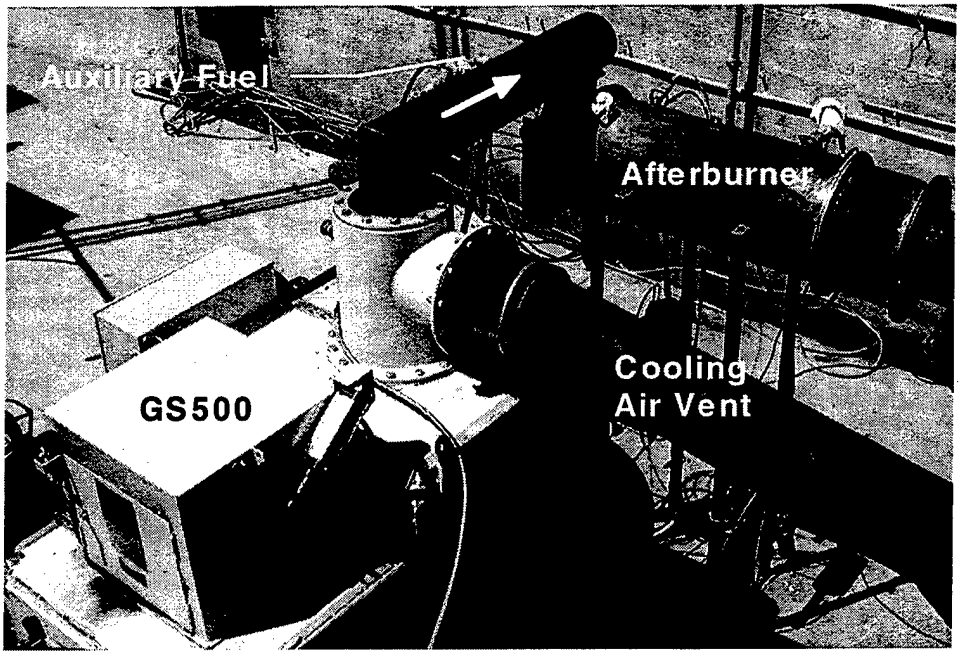

Figure 4. Installation of the Actively Controlled Afterburner and GS500 marine incinerator at EER's Test Site in Irvine, California.

The demonstration afterburner was designed and constructed by NAWCWD for 750 kW capacity and employed elliptical ejectors for pumping hot pyrolysis gases into the afterburner[4]. The design of the afterburner is illustrated in Figure 5. The afterburner was equipped with an acoustically driven primary air jet. The hot pyrolysis products were routed from the transition duct into the hot gas plenum of the burner assembly before being pumped through the fuel ejectors into the air vortices. The double walled afterburner chamber consisted of a 345 mm inner diameter stainless steel liner with an outer air cooling passage. The chamber length was 1,370 mm long. The afterburner's designed firing density is 5,900 kW/m^3. Cooling air from the afterburner liner was added to the exhaust products at the exit of the chamber. The exhaust products then traveled through a 356 mm diameter duct to an induced draft fan.

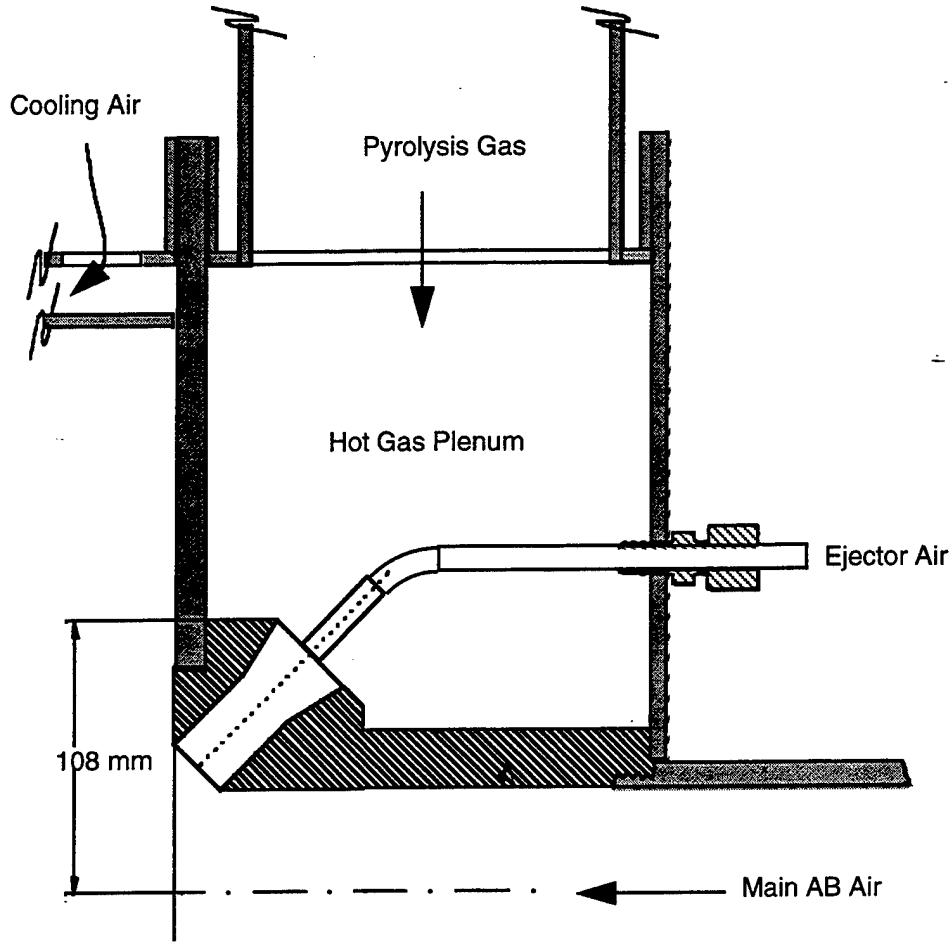

Figure 5. Mark 11a Actively Controlled Afterburner designed for 750 kW nominal operation.

GS500 operational characteristics, including draft pressure and chamber temperature, were displayed on the incinerator control panel. Other parameters were recorded on a strip chart recorder. The pyrolysis gas temperature was measured in the transition duct. The O_2 concentration and gas temperature in the afterburner were monitored 15 mm upstream of the cooling air addition. A multi-point sample rake was used in the afterburner chamber to simultaneously sample from wall-to-wall and average the gas concentrations. This minimizes single point sampling errors due to the stratified concentrations in the afterburner chamber resulting from the afterburner central air injection design. A pressure transducer was mounted to the side wall of the afterburner chamber and was used to record the power spectrum in the chamber. Continuous emission monitoring of the downstream exhaust for CO, THC, NOx, O_2 and carbon

dioxide (CO_2) was conducted at a location that provided 5 diameter lengths downstream and 3 diameter lengths upstream of any flow disturbances to meet US Environmental Protection Agency sampling protocols.

Experimental

The demonstration involved feeding representative solid waste to the GS500 operating in a pyrolysis mode and then burning-out the pyrolysis gases in the Actively Controlled Afterburner. A waste was selected for this demonstration that closely represented the reported target waste stream of the US Navy[5]. A comparison of the demonstration waste versus the target Navy waste and IMO Class 2 waste is presented in Table 1 below.

TABLE 1. COMPARISON OF DEMONSTRATION WASTE TO NAVY AND IMO WASTES

Demonstration Waste		**Target Navy Waste**		**IMO Class 2 Waste**	
	Batch Wt.%		Daily Wt. %		Batch Wt.%
Green Waste	70%	Solid Waste Pulp	0.8%	Food Waste	50
Containing:		Paint Rags	1.%	Rubbish	50
volatiles	*52%*	Wood, Dunnage	7.3%	*Containing:*	
fixed carbon	*32%*	Textiles	9.6%	*paper*	*52%*
moisture	*10%*	Oily Rags	11.9%	*cardboard*	*32%*
ash	*6%*	Plastics	16.4%	*rags*	*10%*
Plastics (PPE)	30%	Cardboard	53%	*plastics*	*6%*
Mixture Contains:					
Moisture	7%		0 to 96%		50%
Ash	4%		NA		7%
Heating Values, MJ/kg					
Batch	25.8	Average	19.4	Batch	10.0
		Maximum	41.1		
		Minimum	0.86		

Cardboard and plastic are the two main components of the target Navy waste which has an average heating value of 19.3 MJ/kg (8,300 BTU/lb). For the demonstration, EER and NAWCWD selected a waste containing 70 percent green waste and 30 percent plastic with a heating value of 25.8 MJ/kg (11,100 BTU/lb). The waste heating value is within the range of that expected for wastes generated onboard US ships and provided a reasonable balance of volatile components, fixed carbon, moisture and ash.

While the target Navy waste presented in Table 1 is an average daily composition and has an average heating value of 19.3 MJ/kg (8,300 BTU/lb). A wide range of batch compositions is possible with heating values ranging from 0.86 to 41.9 MJ/kg (370 to 18,000 BTU/lb). The low heat value compositions are substantially comprised of water which acts to dilute the pyrolysis gas heating value. Previous experiments showed that the afterburner maintained performance when fuel heating value was diluted an order of magnitude. The impact of the waste's moisture content is expected to be minimal provided the heat value is sufficient, above 5.6 MJ/m3 (150 BTU/ft3), to sustain combustion. Evaluation of waste variability and charge rates has been identified for future work.

The demonstration was performed by heating the GS500 on diesel oil firing at 142 kW. When the GS500 reached a target temperature, the afterburner acoustic driver was energized and the afterburner was lit with 585 kW of auxiliary propane fuel. The afterburner stabilized rapidly due to the small volume and low thermal inertia. Then the demonstration began by loading bags of solid waste at regular intervals into the GS500. The target feed rate of waste was 585 kW which corresponds to three times the GS500 certified capacity. For the demonstration waste, that required a solid waste feed rate of 82 kg/hr. During the demonstration, continuous monitoring of afterburner O_2, exhaust gas CO, THC, NOx, O_2 and CO_2, and pyrolysis gas and afterburner chamber temperatures were made.

EER conducted two demonstration tests. One test maintained a constant flow of auxiliary propane fuel to avoid flame out if the pyrolysis gas heat value dropped. The other test

attempted to vary auxiliary propane input to maintain a constant oxygen (O_2) demand in the pyrolysis fuel. Because the solid waste is charged in batches, the release of pyrolysis gases fluctuates between charges. Upon charging the waste, volatiles and moisture are rapidly released. Over time the remaining fixed carbon species are partially oxidized and released. This results in rapid cycling of pyrolysis gas heat value and afterburner O_2 demand upon initial charging, and a steady increase in O_2 demand over time as the fixed carbon releases. The pyrolysis gas heat value is therefore highly variable over short charging cycles due to volatiles and over the long term due to fixed carbon release. The demonstration tests conducted focused more on the short term performance and highly variable pyrolysis heat values.

Some difficulties were encountered in operating the GS500 in starved-air mode. The GS500 is designed for induced draft operation which pulls excess air into the chamber through numerous gaps and opening in the chamber refractory walls. These gaps and openings were sealed as much as possible and the GS500 negative draft was reduced to only 1 mm of water column for starved-air operation, however, pyrolysis gas products were still seen to leak into the cooling air shell that vented to atmosphere. Unfortunately therefore, accurate quantification of the quantity of pyrolysis products from the GS500 was difficult. However, the quality of pyrolysis gas was noticed to be heavily laden with soot and even char particles very representative of solid waste pyrolysis gases.

Results

Both demonstration tests were short tests, just over 30 minutes, due to unrelated shutdowns. Shutdown occurred in one case by the PLC controller for a low draft condition and in another by the operator because of an excessive temperature condition in the downstream exhaust duct. During the tests, the afterburner demonstrated the ability to control emissions extremely well despite large fluctuations in pyrolysis gas compositions. The CO, THC and NO emission data for the demonstration test involving constant auxiliary fuel input, Test A, are presented in Figure 6. The waste was charged in 9.5 kg bags every 7 minutes at the times indicated by the arrows on the plot. The CO levels are seen to rise 8 minutes after the first waste charge and continue fluctuating with apparent

release of volatiles from the each successive waste charge. At the peak pyrolysis gas O_2 demand and corresponding peak CO, excess air in the afterburner was as low as 5 percent which is well below the optimum excess air levels. Still the CO and THC emissions were relatively low. The CO emissions, replotted in Figure 7, are shown to be well below the GS500 certified levels and IMO standard. THC were not seen to fluctuate and remained at the detection limit, <2 ppm.

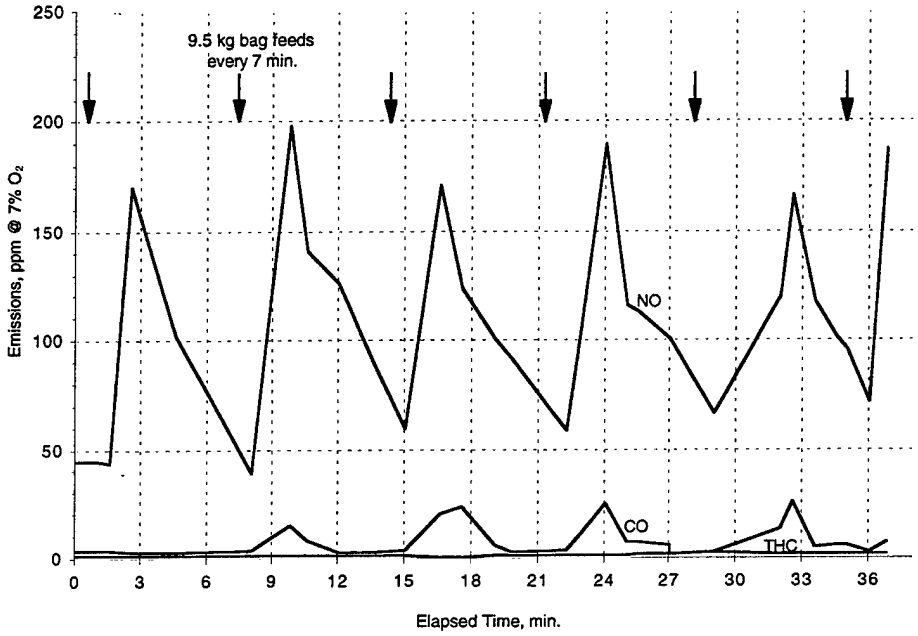

Figure 6. Demonstrated emission performance data of the Actively Controlled Afterburner operating on solid waste with a constant auxiliary fuel input of 392 kW.

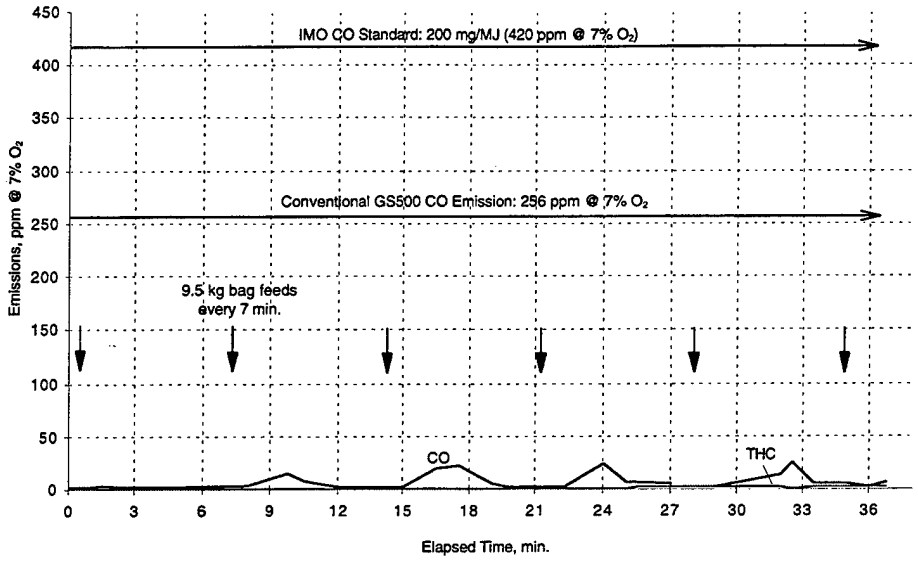

Figure 7. Comparison of the Actively Controlled Afterburner CO emissions to certified GS500 incinerator performance and IMO CO standards. THC emissions are also shown. Operation was with solid waste and a constant auxiliary fuel input of 392 kW.

The other demonstration test, Test B, was operated with a varying amount of auxiliary fuel in an attempt to maintain the O_2 demand of the pyrolysis gas. The auxiliary fuel was manually controlled while monitoring the O_2 concentrations in the afterburner. The feedback approach involved a 30 second delay that made real-time control difficult. The CO, THC and NO emissions for this demonstration test are presented in Figure 8. The waste charge was reduced to 4.3 kg bags charged every 3 minutes to dampen the oscillations and assist in control of the pyrolysis gas O_2 demand. In this test the CO levels are seen to rise soon after the first waste charge and fluctuate less with each charge than during the Test A. However, auxiliary fuel was varied throughout the test. Test records indicate that the high CO levels that occurred after 25 minutes were caused by an extreme reduction in auxiliary fuel that produced a low O_2 demand (heat value) pyrolysis gas. The recorded excess air level at peak CO emissions were as high as 110 percent. In contrast to the constant auxiliary fuel test where peak CO occurred at the high extreme of pyrolysis gas O_2 demand, in this test, peak CO occurred at the low extreme of pyrolysis gas O_2 demand. The CO emissions, replotted in Figure 9, are shown to be well below the GS500

certified levels and IMO standard. THC were not seen to fluctuate and remained at the detection limit, <2 ppm.

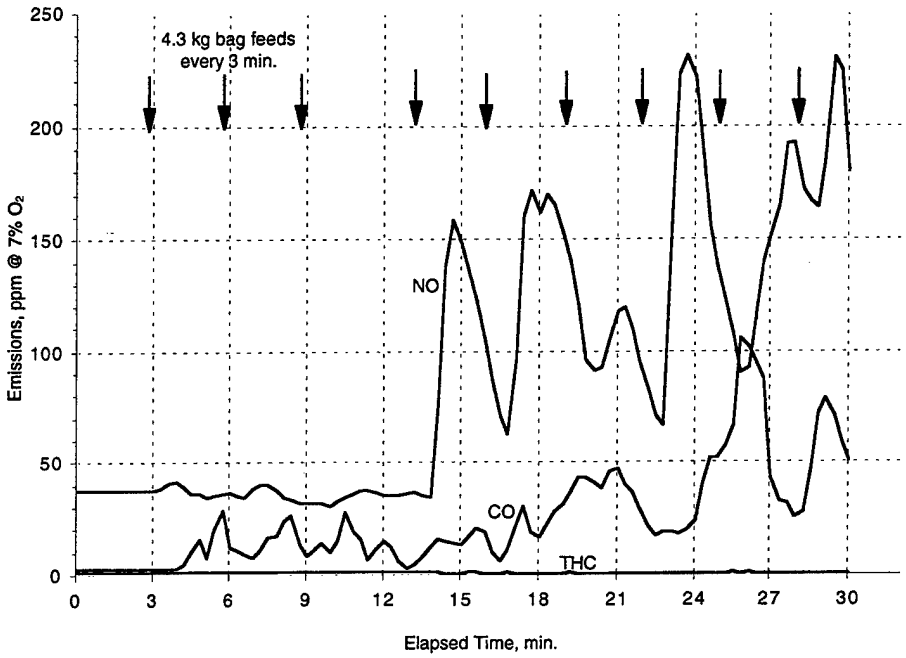

Figure 8. Demonstrated emission performance data of the Actively Controlled Afterburner operating on solid waste while auxiliary fuel input was varied in an attempt to maintain pyrolysis gas oxygen demand. The average auxiliary fuel flow was 308 kW.

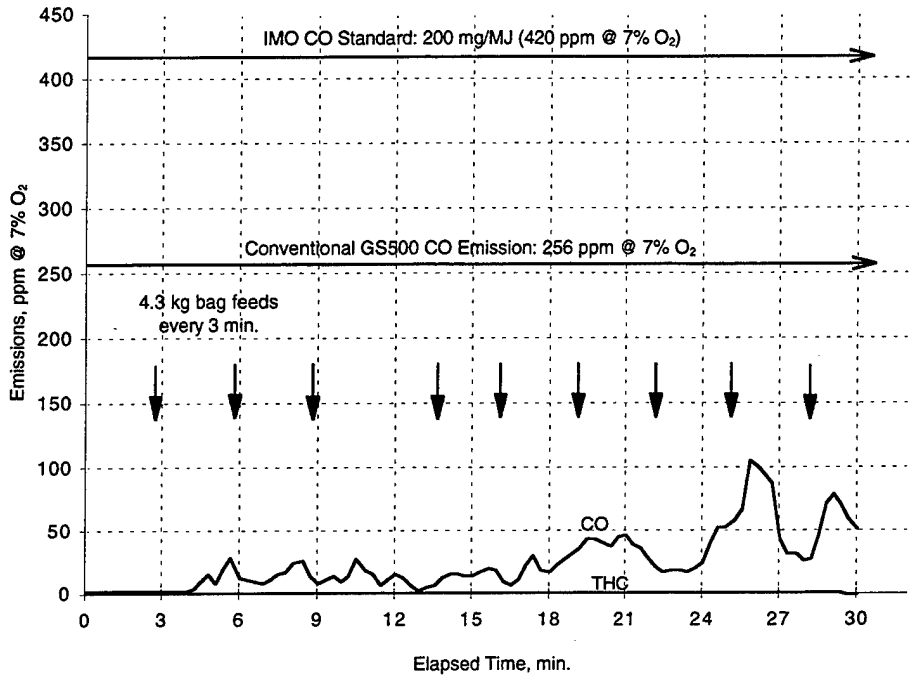

Figure 9. Comparison of the Actively Controlled Afterburner CO emissions to certified GS500 incinerator performance and IMO CO standards. THC emissions are also shown. Operation was with solid waste and a varying amount of auxiliary fuel in an attempt to maintain the pyrolysis gas oxygen demand. The average auxiliary fuel input was 308 kW.

Discussions

The demonstration tests showed that gaseous products from the pyrolysis of realistic solid waste could be effectively burned out in the Actively Controlled Afterburner. Although some limitations were experienced in operating the GS500 in a starved-air mode, generally the results are clear: Reaction products from the pyrolysis of solid waste are effectively handled by the afterburner and significant CO reductions below IMO standards were achieved.

The fluctuating emissions data suggest to the general limitations of the demonstration which did not include necessary controls for maintaining pyrolysis gas heat value within a preferred range. A cumulative plot (Figure 10) of CO data versus O_2 concentration for both tests illustrates the influence of pyrolysis gas O_2 demand (heat value) on CO

emissions. The multi-variant plot identifies the importance of controlling pyrolysis gas O_2 demand. As O_2 demand increased and excess O_2 drops in the exhaust, CO emissions increased. The CO increase is even more significant when O_2 demand decreases. A minimum CO emission is achieved at an O_2 concentration around 6 percent. This plot illustrates the need for a rapid-response, feed-forward O_2 demand sensor to optimize the system for operating on a wide range of pyrolysis gas heating values.

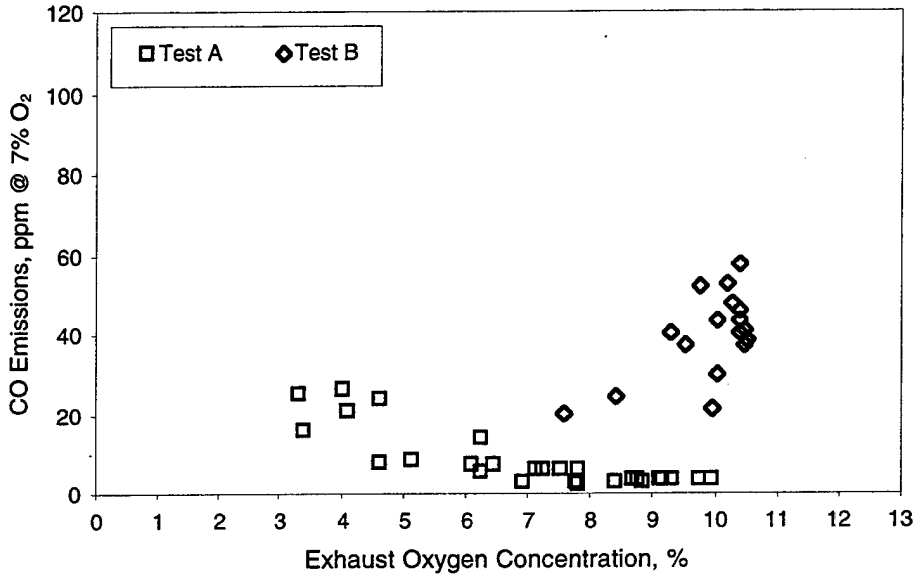

Figure 10. CO emissions correlated to exhaust oxygen concentration. Plot includes entire demonstration data of Test A operating at a constant auxiliary fuel input of 392 kW and a portion of the demonstration data of Test B when auxiliary fuel input was kept constant at 308 kW.

During the demonstration, the waste feed rate was 82 and 86 kg/hr for the constant and variable auxiliary fuel demonstration tests, respectively, corresponding to 580 kW and 615 kW. The waste feed, on a heat value basis, was over 3 times the GS500 certified waste feed capacity of 195 kW. Throughout the demonstration periods, the CO emissions remained well below the GS500 certified levels and THC emissions were at the detection limit (<2 ppm). The summary of operation and performance for the two demonstration tests are presented in Table 2.

The afterburner operated with average excess air levels of 35 to 45 percent, although excess air levels ranged from 5 to 110 percent due to the fluctuating O_2 demand of the pyrolysis gas and variations in the auxiliary fuel feed. Average NO emissions were 111 and 92 ppm

TABLE 2. OPERATION AND PERFORMANCE OF THE INTEGRATED GS500 AND ACOUSTIC AFTERBURNER

	Units	Test A	Test B
Operation			
Solid Waste Feed	kW	580	615
Auxiliary Propane	kW	392	308
Diesel Oil Burner	kW	142	142
Afterburner Temperature	°C	1,200	1,120
Afterburner Oxygen	%	5.5	6.6
Performance			
Carbon Monoxide	ppm, @ 7% O_2	8.5	28
Total Hydrocarbons	ppm, @ 7% O_2	1.8	1.2
Soot Number	Bacharach No.	<3 (a)	<3 (a)
Carbon-in-Ash	%	NA	NA
Oxides of Nitrogen	ppm, @ 7% O_2	111	92

Test A - constants auxiliary fuel input
Test B - variable auxiliary fuel input
NA - not available
(a) - no detectable exhaust plume

@ 7% O_2 for the first and second test, respectively. The NO emissions correlated directly with excess O_2 levels (Figure 11) indicating that finer control of the pyrolysis product O_2 demand and operation of the afterburner at optimal excess air levels will likely eliminate NO spikes and result in lower average NO emissions. The data in Figure 11 show that NO concentrations are higher for the case where auxiliary fuel was lower even for the same exhaust O_2 concentration. One would expect that NO would increase with auxiliary fuel flow as it has a higher volumetric heat content and would raise the combustion temperature. However, auxiliary fuel is also devoid of fuel nitrogen while the solid waste

contains fixed nitrogen species that can contribute to NO formation. The ratio of solid waste pyrolysis gas to auxiliary fuel is nearly 25 percent greater and as a result may be an important factor contributing to the higher NO concentrations under reduced auxiliary fuel usage.

IMO standards require no visible exhaust plumes. This corresponds to a Bacharach number of less than 3. During demonstration of the afterburner, a certified Bacharach measurement or opacity measurement was not conducted, however, no visible plume was observed even with as little as 20 percent excess air in the stack gas. This compared favorably to the

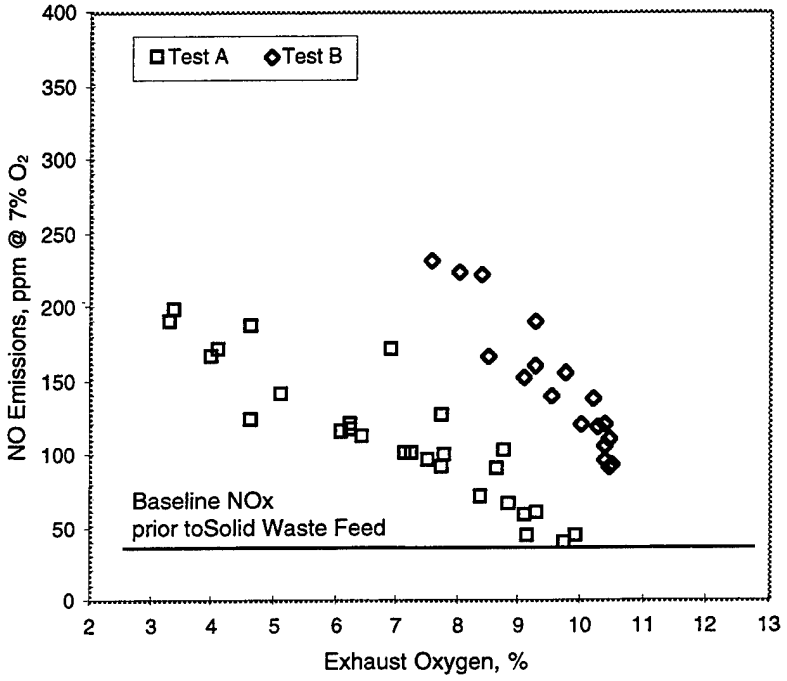

Figure 11. NO emissions correlated to exhaust oxygen concentration. Plot includes entire demonstration data of Test A operating at a constant auxiliary fuel input of 392 kW and a portion of the demonstration data of Test B when auxiliary fuel input was kept constant at 308 kW.

GS500 certified Bacharach no. of 2.8 that was achieved with over 250 percent excess air diluting the stack gas.

The demonstration did not include a burn-down cycle that essentially burns out carbon-in-ash prior to shutdown. For this reason, carbon-in-ash analyses were not conducted. In a fully coupled afterburner system a standard burn-down cycle would be employed to reduced carbon-in-ash to acceptable standards.

In summary, the demonstration met the objective of increasing the waste throughput capacity while reducing emissions. Future items identified for evaluation include waste composition variability, waste charge rate limitations, plume soot measurements, and carbon-in-ash levels. Additionally some hardware changes and supplementary system were identified to improve the system and these include, (1) the use of an air tight primary chamber, (2) deployment of a pyrolysis gas O_2 demand (heating value) control system, and (3) integration of an carbon-in-ash burn-down cycle.

Acknowledgments

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